Soil Organic Matter Pools during Early Adoption of Conservation Tillage in Northwestern Canada

A. J. Franzluebbers and M. A. Arshad*

ABSTRACT

Changes in soil organic matter (SOM) pools during adoption of reduced (RT) or zero tillage (ZT) can influence soil physical properties, nutrient cycling, and CO_2 flux between soil and atmosphere. We determined soil organic C (SOC), soil microbial biomass C (SMBC), basal soil respiration (BSR), and mineralizable N to a depth of 200 mm at the end of 3, 5, and 6 yr after implementation of tillage management on a Falher clay (fine, montmorillonitic, frigid Typic Natriboralf) near Rycroft, Alberta, in a canola (*Brassica campestris* L.)-wheat (*Triticum aestivum* L.)-barley (*Hordeum vulgare* L.)-fallow cropping system. At the end of 6 yr, SOC was not different among tillage regimes and averaged 8.6 kg m^{-2}. At the end of 3 and 5 yr, SMBC was not significantly different among tillage regimes, but at the end of 6 yr SMBC was 7% greater in RT and 9% greater in ZT than in conventional tillage (CT). Basal soil respiration and mineralizable N at the end of 6 yr were not different among tillage regimes following barley and averaged 2.7 g CO_2-C m^{-2} d^{-1} and 5.0 g inorganic N m^{-2} 24 d^{-1}, respectively. However, BSR following fallow was 2.2, 2.5, and 2.6 g CO_2-C m^{-2} d^{-1} in CT, RT, and ZT, respectively. Mineralizable N following fallow was 5.8 g inorganic N m^{-2} (24 d)$^{-1}$ in RT and ZT and 7.3 g inorganic N m^{-2} (24 d)$^{-1}$ in CT. At 0 to 50 mm, there was no significant increase in SOC at the end of 6 yr, a 17 to 36% increase in SMBC, and a 12 to 69% increase in BSR with ZT compared with CT, depending on rotation phase. Relatively small changes in SOM pools with adoption of conservation tillage may be attributable to the large amount of SOM initially present and the cold, semiarid climate that limits SOM turnover.

S OIL ORGANIC MATTER plays a critical role in nutrient cycling, water retention, and overall soil quality (Follett et al., 1987). Loss of SOM leads to a reduction in soil tilth with subsequent loss of soil productivity (Karlen et al., 1990; Bauer and Black, 1994). On agricultural soils with low to medium clay content, loss of SOM can be minimized with the use of conservation tillage, which allows crop residues to remain on the soil surface and minimizes soil disturbance (Doran, 1987; Arshad et al., 1990; Ismail et al., 1994). Conversion from CT to ZT resulted in an increase in SOC ranging from 0.2 to 1.5 kg m^{-2} within the surface 150 to 200 mm of low to medium clay content soils at mesic and thermic locations in the USA with mean annual precipitation >700 mm after 5 to 20 yr (Doran, 1987; Beare et al., 1994; Ismail et al., 1994; Franzluebbers et al., 1995b,c). However, after >5 yr of ZT management, small or no differences in SOC were observed in the surface 100 to 200 mm of low to medium clay content soils at mesic and frigid locations (Carter and Rennie, 1982; Havlin et al., 1990).

Adoption of conservation tillage in the Peace River region of northern Alberta, Canada, dominated by high clay content soils, is growing because of concerns about soil erosion, water conservation, and decreasing margin of profit with CT. Little information is available on changes in SOM of high clay content soils during the conversion from CT to RT or ZT management. In an Australian Vertisol with >60% clay, SOC to a depth of 100 mm was 1.5 to 1.8 g kg^{-1} greater under ZT than under CT at the end of 13 yr (Dalal, 1989), but in the same study was not different between tillage regimes at the end of 20 yr (Dalal et al., 1991). Cracking clay soils

have self-tilling properties that may limit the buildup of surface SOM. Therefore climatic conditions, especially the amount and frequency of precipitation, which determines the extent of cracking in these soils, may reduce the effect of ZT management on SOM accumulation near the soil surface.

Early changes in SOM content with conversion from CT to RT or ZT management may be small and detectable only by monitoring the active fractions of SOM, i.e., the SMB (Powlson et al., 1987) and mineralizable C and N. The decline in SMBC was greater than measurable changes in SOC during the first 3 yr after plowing a meadow in Quebec (Angers et al., 1992). Soil organic C was similar between tillage regimes, but SMBC was ≈30% greater in ZT than in CT after 10 yr in Ohio (Staley et al., 1988).

Knowledge of the changes in SMB and mineralizable C and N is of further interest for estimating the nutrient supplying capacity of soil, in which the SMB acts as the agent of mineralization–immobilization of nutrients from SOM and crop residues. Crop fertilization to attain economically optimum yield without serious risk to ground and surface water quality during a change in tillage management must account for associated changes in the active fractions of SOM. Our objective was to determine mineralizable C and N, SMBC, and SOC in the plow layer of a clay soil in northern Alberta under CT, RT, and ZT management 3, 5, and 6 yr after initiation.

MATERIALS AND METHODS

A field experiment comparing CT, RT, and ZT management systems was initiated on a Falher clay derived from lacustrine deposits near Rycroft, Alberta (55° 43' N, 118° 41' W) in 1989. In 1989, SOC of the 0- to 150-mm depth averaged 40 g kg^{-1} and soil pH (10 g soil, 20 mL 0.01 M CaCl$_2$) was 5.4. To a depth of 200 mm, clay and silt contents were 63 and 31%, respectively. Long-term annual temperature is 2°C and precipitation is 449 mm. From May to September, temperature and precipitation average 12°C and 264 mm, respectively. The experimental design was a randomized block with four replications. Plots measured 12 by 39 m. Variance due to tillage and previous crop within each year and soil depth was analyzed with the general linear model procedure of SAS (SAS Institute, 1990). Soil properties were deemed significantly different at $P \leq 0.05$.

Conventional tillage consisted of a heavy-duty disking to a depth of 100 to 120 mm during the autumn followed by two cultivations in spring to a depth of 70 to 100 mm. Reduced tillage consisted of a single shallow disking to a depth of 70 to 100 mm in spring prior to seeding. Zero tillage consisted of harrowing following harvest (without significant soil disturbance) to evenly distribute straw and spraying glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine] to control weeds prior to seeding. Crops were grown in a canola–wheat–barley–fallow sequence with all phases present each year. The fallow was managed to control weeds with one to three disk operations to a depth of 70 to 100 mm in CT, field pea (*Pisum sativum* L.) incorporated to a depth of 70 to 100 mm as green manure at full bloom in July–August in RT, and herbicide application in ZT. All crops were sown in mid-May at recommended seeding rates for the region. Fertilizer was applied based on soil test results, varying from 0 to 10 g N m^{-2} and

2 to 3.5 g P m^{-2} (all crops) and 1.3 g S m^{-2} (canola and pea only).

Soil samples were collected following the fallow and barley phases of the rotation. In early May prior to field operations in 1992 (3 yr) and 1994 (5 yr), three soil cores (50-mm diam.) were composited from the 0- to 100- and 100- to 200-mm depths. Samples collected prior to seeding should have minimized short-term effects of crop root and residue additions from the previous year. Soil was oven dried (60°C), ground in a mill to pass a 2-mm screen, and stored in an air-dried state until 1995. In late April of 1995 (6 yr), eight soil cores (25 mm diam.) were composited from the 0- to 50-, 50- to 125-, and 125- to 200-mm depths. Soil was air dried and gently crushed to pass a 5.6-mm screen. Soil bulk density and water-filled pore space at the end of 6 yr were calculated from an oven-dried subsample (60°C, 48 h) and volume of the coring device. Soil organic C at the end of 6 yr was determined using the modified Mebius method (Nelson and Sommers, 1982).

Oven-dried soil collected at the end of 3 and 5 yr (10-g subsamples) was weighed into three 30-mL plastic vials and one 30-mL glass beaker and brought to field capacity (0.40–0.45 kg water kg^{-1} soil). The four subsamples were placed in a 1-L glass jar along with a vial containing 10 mL of 0.3 M NaOH to trap evolved CO$_2$ and a vial containing 10 mL of water to maintain high humidity. Soil was incubated at 22.5 ± 1°C for 24 d and CO$_2$–C evolved was determined by titration with HCl at 3, 10, and 24 d, replacing the alkali trap each time (Anderson, 1982). Air-dried soil collected at the end of 6 yr (a 40-g subsample in a 50-mL beaker and a 20-g subsample in a 30-mL glass beaker) was moistened (0.40 kg water kg^{-1} soil) and incubated in the presence of 10 mL of 0.55 M NaOH at 25 ± 0.5°C for 24 d, with alkali traps changed at 3, 10, and 24 d. Cumulative CO$_2$–C evolution was fit to a two-pool model using nonlinear regression of the form:

$$C_t = C_f (1 - e^{-kt}) + BSR \, t$$

where C_t = cumulative C mineralization (mg C kg^{-1} soil) under standard conditions at time t (d), C_f = C mineralization due to the flush after rewetting of dried soil (mg C kg^{-1} soil), k = nonlinear mineralization constant (d^{-1}), and BSR = basal soil respiration (mg C kg^{-1} soil d^{-1}). A second method for calculating BSR was also determined from the rate of C mineralization between 10 and 24 d and is reported in the following.

For determination of SMBC, the 20-g subsample was removed at 10 d of incubation (Franzluebbers et al., 1996), placed in a vacuum dessicator, and fumigated with chloroform following the procedure of Jenkinson and Powlson (1976). At the end of 24 h, the beaker of soil was placed into a 1-L glass jar along with vials containing alkali and water and incubated at 22.5 ± 1°C (3 and 5 yr) or 25 ± 0.5°C (6 yr) for 10 d. The flush of CO$_2$–C released on fumigation was determined from titration with HCl and corresponded to the size of the SMBC according to the equation (Voroney and Paul, 1984):

$$SMBC = (mg \; CO_2 - C \; kg^{-1} \; soil)_{fumigated}/k_C$$

where k_C = 0.41. Specific respiratory activity of SMBC was estimated by dividing BSR by SMBC.

Inorganic N (NH$_4$–N + NO$_3$–N + NO$_2$–N) concentration of soil collected at the end of 3 and 5 yr that was incubated for 0, 3, 10, and 24 d was determined after freezing (−20°C) to stop microbial activity. Ten milliliters of 2 M KCl was added to the soil in the 30-mL vials, the slurry shaken for 1 h, and the filtered extract frozen until analyzed for NH$_4$–N and NO$_3$–N + NO$_2$–N using autoanalyzer techniques with a modified indophenol blue method with citrate buffer and a Cd reduction method, respectively (Bundy and Meisinger, 1994).

Soil collected at the end of 6 yr was oven dried (60°C, 48 h) at 0 and 24 d of incubation and sieved to pass a 2-mm screen. A 5-g subsample was shaken with 10 mL of 2 M KCl for 1 h, filtered, and the extract analyzed for inorganic N as described above.

RESULTS AND DISCUSSION

Soil Physical Properties

Soil bulk density following barley was greater under CT than under RT or ZT in the 0- to 50-mm depth at the end of 6 yr (Table 1). Following fallow, bulk density was lower in CT than in RT or ZT at 50 to 125 mm, suggesting that the effect of frequent tillage during fallow persisted through the long ($\approx$6 mo), cold winter.

Water-filled pore space following barley was not different among tillage regimes at any depth (Table 1), suggesting that tillage regimes at the end of 6 yr had similar water retention capacity near the soil surface after spring snowmelt. However, following fallow, water-filled pore space was greater in ZT than in CT or RT at 0 to 50 mm and greater in ZT and RT than in CT at 50- to 125- and 125- to 200-mm soil depths. Frequent tillage to control weeds during the fallow of CT may have had a negative impact on the capacity of soil to retain water perhaps due to aggregate destruction or alteration of pore size distribution. The lower bulk density in CT indicated that there were more large pores that would have drained freely after snowmelt.

Soil Organic Carbon

Tillage management had no significant effect on SOC at the end of 6 yr. Soil organic C averaged across tillage regimes and crop phases was 47.8 g kg^{-1} at the 0- to 50-mm depth, 40.3 g kg^{-1} at the 50- to 125-mm depth,

and 27.6 g kg^{-1} at the 125- to 200-mm depth. At a depth of 0 to 200 mm, SOC averaged 36.9 g kg^{-1} (8.6 kg m^{-2}).

Carbon input to the soil from 1989 to 1994, estimated from crop yields, averaged 130 ± 45 g m^{-2} yr^{-1} in CT, 145 ± 32 g m^{-2} yr^{-1} in RT, and 132 ± 41 g m^{-2} yr^{-1} in ZT (unpublished data, 1995). These estimates were derived assuming (i) stover and grain of all crops contained 42% C, (ii) subsurface C input was 42% of total aboveground C input (Whipps, 1990), (iii) grain and stover production during the 6-yr period was represented by values from 1989 and 1991 (Arshad et al., 1994, 1995) and 1992 and 1994 (unpublished data, 1995) (estimates were unavailable during 1990 [canola] and 1993 [all crops] due to climatic conditions that prevented sampling), and (iv) negligible C input occurred during the fallow phase (pea green manure production in RT was not measured, although green manure C input may have added an additional 40 to 60 g m^{-2} yr^{-1} to these estimates [unpublished data, 1995]). No measurable difference in SOC among tillage regimes at the end of 6 yr was probably due to the similarity in C input, large background of SOC initially present, and low annual temperature that limited any stimulus for greater C mineralization due to tillage.

In a loam from Saskatchewan, SOC to a depth of 150 mm was 2.3 kg m^{-2} in a wheat–fallow rotation under CT and 3.2 kg m^{-2} in continuous wheat under ZT at the end of 6 yr (Campbell et al., 1989). The low initial SOC content and differences in C input between tillage regimes may have contributed to the increase in SOC. In a clay loam from Saskatchewan, SOC to a depth of 200 mm was 10.5 kg m^{-2} under CT and 11.4 kg m^{-2} under ZT at the end of 12 yr, whereas other soils from Alberta and Saskatchewan managed with ZT had similar or lower SOC content than soils managed with CT (Carter and Rennie, 1982). In a silt loam from British Columbia, SOC was 7.3 g kg^{-1} greater under ZT than under CT at a depth of 0 to 75 mm at the end of 10 yr (Arshad et al., 1990). There are fewer reports of changes in SOC due to tillage regime in the frigid than the thermic or mesic regions (Rasmussen and Collins, 1991), indicating that annual temperature is a primary determinant of potential changes in SOM with changes in tillage management.

Table 1. Soil bulk density and water-filled pore space of a Falher clay at the end of 6 yr of tillage management in a canola-wheat-barley-fallow† sequence.

Tillage/previous crop	Soil depth (mm)			
	0 to 50	50 to 125	125 to 200	0 to 200
	Soil bulk density (Mg m^{-3})			
Convention tillage				
Barley	1.06	1.22	1.23	1.19
Fallow	1.02	1.06	1.23	1.11
Reduced tillage				
Barley	1.01	1.18	1.28	1.17
Fallow	1.02	1.18	1.28	1.17
Zero tillage				
Barley	1.00	1.22	1.28	1.18
Fallow	1.00	1.18	1.28	1.17
LSD$_{(P \leq 0.05)}$	0.05	0.05	0.06	0.04
	Water-filled pore space (m^3 m^{-3})			
Conventional tillage				
Barley	0.52	0.79	0.82	0.73
Fallow	0.46	0.61	0.76	0.63
Reduced tillage				
Barley	0.51	0.74	0.84	0.72
Fallow	0.46	0.74	0.83	0.70
Zero tillage				
Barley	0.54	0.78	0.87	0.75
Fallow	0.55	0.73	0.83	0.73
LSD$_{(P \leq 0.05)}$	0.06	0.06	0.06	0.05

† Fallow weed control was mechanical in conventional tillage, pea green manure in reduced tillage, and chemical in zero tillage.

Soil Microbial Biomass Carbon

Soil microbial biomass C was not significantly different among tillage regimes at the end of 3 or 5 yr (data not shown), but averaged across rotation phase at the end of 6 yr was 192 g m^{-2} in CT, 206 g m^{-2} in RT, and 210 g m^{-2} in ZT to a depth of 200 mm. Although not significant, SMBC to a depth of 200 mm under ZT was 10 and 17 g m^{-2} larger than under CT at 3 and 5 yr, respectively. Carter and Rennie (1982) found greater SMBC under ZT than under CT at a depth of 0 to 100 mm in a clay loam in Saskatchewan at the end of 4 yr, but no differences were detected between tillage regimes in three other soils managed for 2, 12, or 16 yr.

The portion of SOC as SMBC following fallow was

greater in ZT than in CT at the 0- to 50-mm depth, but not different between tillage regimes at 50- to 125- and 125- to 200-mm depths (Table 2). At a depth of 0 to 200 mm, the portion of SOC as SMBC following fallow tended to be higher with RT and ZT than with CT, but was not different among tillage regimes following barley. This tendency indicates that frequent tillage during the fallow in CT may have created more drying–wetting stress, thereby reducing the capacity of soil to support SMBC. The tendency for a greater portion of SOC as SMBC following barley than following fallow suggests that frequent C input via rhizodeposition and crop residue addition was necessary to maintain a high level of SMBC. The portion of SOC as SMBC in this study was ≈37% of average values determined for soils in Texas (Franzluebbers et al., 1995b,c). The smaller active fraction of SOM in this northern soil suggests that the pool of resistant SOM is greater than in more temperate climates due to lower soil temperature or the more extensive freezing–thawing and drying–wetting that rendered SOM biogeochemically less available for microbial growth and activity.

Table 2. Portion of soil organic C (SOC) as soil microbial biomass C (SMBC) and as basal soil respiration (BSR) and specific respiratory activity of SMBC of a Falher clay at the end of 6 yr of tillage management in a canola-wheat-barley-fallow† sequence.

Tillage/previous crop	Soil depth (mm)			
	0 to 50	50 to 125	125 to 200	0 to 200
	Portion of SOC as SMBC (mg SMBC g^{-1} SOC)			
Conventional tillage				
Barley	27.3	24.4	22.2	24.5
Fallow	21.1	22.0	21.0	21.4
Reduced tillage				
Barley	24.9	23.1	24.7	24.1
Fallow	25.1	24.1	23.9	24.3
Zero tillage				
Barley	30.4	23.9	23.0	25.3
Fallow	27.3	21.9	23.4	23.9
LSD$_{(P \leq 0.05)}$	3.7	3.2	5.0	3.6
	Portion of SOC as BSR (mg CO$_2$-C g^{-1} SOC d^{-1})			
Conventional tillage				
Barley	0.64	0.30	0.16	0.35
Fallow	0.32	0.28	0.14	0.25
Reduced tillage				
Barley	0.51	0.24	0.18	0.30
Fallow	0.45	0.29	0.16	0.29
Zero tillage				
Barley	0.70	0.23	0.18	0.34
Fallow	0.52	0.23	0.17	0.30
LSD$_{(P \leq 0.05)}$	0.15	0.07	0.02	0.07
	Specific respiratory activity (mg CO$_2$-C g^{-1} SMBC d^{-1})			
Conventional tillage				
Barley	23.6	12.3	7.2	14.4
Fallow	15.4	12.7	6.8	11.6
Reduced tillage				
Barley	20.3	10.6	7.1	12.4
Fallow	17.7	11.7	6.7	12.0
Zero tillage				
Barley	22.8	9.7	7.7	13.4
Fallow	19.0	10.4	7.4	12.4
LSD$_{(P \leq 0.05)}$	3.6	1.9	1.5	1.4

† Fallow weed control was mechanical in conventional tillage, pea green manure in reduced tillage, and chemical in zero tillage.

Basal Soil Respiration and Mineralizable Nitrogen

Basal soil respiration estimated with the two methods was closely related; the linear rate between 10 and 24 d yielding 5 ± 3% greater values than using the nonlinear equation ($r^2 = 0.99$, $n = 18$). Basal soil respiration at a depth of 0 to 200 mm following barley was not different among tillage regimes, but following fallow was greater in ZT than in CT at the end of 6 yr (Table 3). At the 0- to 50-mm depth following fallow, BSR was greater in ZT than in RT or CT, but at 50- to 125-mm depth it was lower in ZT than in CT. The large decrease in BSR with depth indicates that available substrates for mineralization were concentrated near the surface in this soil.

Basal soil respiration to a depth of 200 mm averaged across tillage regimes following barley was 3.08, 3.23, and 2.75 g mineralizable C m^{-2} d^{-1} at the end of 3, 5, and 6 yr, respectively, indicating that no consistent shift in BSR occurred with time. Cumulative C mineralization to a depth of 200 mm averaged 97, 115, and 88 g CO$_2$-C m^{-2} (24 d)$^{-1}$ at the end of 3, 5, and 6 yr,

Table 3. Basal soil respiration (BSR), mineralizable N, and C:N ratio of mineralizable fraction during a 24 d incubation of a Falher clay at the end of 6 yr of tillage management in a canola-wheat-barley-fallow† sequence.

Tillage/previous crop	Soil depth (mm)			
	0 to 50	50 to 125	125 to 200	0 to 200
	Basal soil respiration (mg CO$_2$-C kg^{-1} soil d^{-1})			(g m^{-2} d^{-1})‡
Conventional tillage				
Barley	28.1	10.7	4.2	2.87
Fallow	15.9	12.2	4.3	2.17
Reduced tillage				
Barley	24.6	9.9	4.6	2.56
Fallow	20.8	11.6	4.3	2.50
Zero tillage				
Barley	31.5	8.5	4.9	2.81
Fallow	26.8	9.5	4.5	2.61
LSD$_{(P \leq 0.05)}$	5.6	1.5	0.8	0.39
	Mineralizable N (mg kg^{-1} soil 24 d^{-1})			(g m^{-2} 24 d^{-1})
Conventional tillage				
Barley	22.2	21.0	18.1	4.78
Fallow	43.2	30.6	29.2	7.29
Reduced tillage				
Barley	24.7	23.6	18.3	5.08
Fallow	31.7	25.3	20.3	5.78
Zero tillage				
Barley	27.8	22.0	18.2	5.13
Fallow	28.8	27.2	21.5	5.89
LSD$_{(P \leq 0.05)}$	5.6	2.8	7.8	0.92
	C:N ratio of mineralizable fraction			
Conventional tillage				
Barley	38.8	15.7	8.7	18.8
Fallow	12.7	13.7	6.4	10.8
Reduced tillage				
Barley	31.0	13.6	9.7	16.5
Fallow	20.9	14.7	8.3	14.1
Zero tillage				
Barley	35.5	12.7	10.3	17.9
Fallow	31.0	11.8	8.4	15.2
LSD$_{(P \leq 0.05)}$	9.6	2.4	1.9	2.7

† Fallow weed control was mechanical in conventional tillage, pea green manure in reduced tillage, and chemical in zero tillage.
‡ Content on an area basis was calculated from the equation: [concentration (mg kg^{-1})]·[bulk density (Mg m^{-3})]·[sampling depth (m)].

respectively. Little change in biological activity with time averaged across tillage regimes was expected since this soil was under CT for several decades prior to implementation of tillage regimes.

Specific respiratory activity of SMBC was not affected by tillage regime at a depth of 0 to 200 mm at the end of 3 and 5 yr (data not shown) or at the end of 6 yr (Table 2). However, at the 0- to 50-mm depth following fallow, specific respiratory activity was greater in ZT than in CT, but at the 50- to 125-mm depth it was less in ZT than in CT after both crop phases. A similar redistribution of microbial activity with depth was observed for the portion of SOC as BSR (Table 2). The enrichment in microbial activity at 0 to 50 mm in ZT and at 50 to 125 mm in CT can be attributed to crop residue placement. The decrease in specific respiratory activity and portion of SOC as BSR with increasing soil depth further suggests (i) greater turnover of SMBC at the soil surface perhaps due to more frequent and severe drying–wetting or (ii) accumulation of more resistant SOM at lower depths. If more resistant SOM has accumulated with depth, then the likelihood of higher and more uniform moisture content with depth may have allowed a larger pool of SMB with lower specific respiratory activity to exist.

Specific respiratory activity of SMBC and the portion of SOC as BSR in this clay soil from Alberta were ≈10 to 50% of those in a silty clay loam in Texas (Franzluebbers et al., 1994), suggesting that soils in northern regions contain a greater resistant and a smaller active fraction of SOM. Further research is needed to elucidate those chemical fractions that relate to this difference in potential biological activity across an environmental gradient. Greater total SOM content in northern than southern regions of North America appears to be a consequence of lower annual soil temperature (Jenny, 1941; Kemper and Koch, 1966) such that a greater portion of the rapidly decomposable fractions of SOM are mineralized during the short time period suitable for microbial activity than the resistant fractions, leaving behind more resistant compounds. The community of microorganisms may also have been ecologically selected for those organisms able to act primarily on the rapidly decomposable fractions of SOM and plant residues because of the temperature constraint.

Mineralizable N to a depth of 200 mm was not different among tillage regimes and averaged 3.9 and 5.0 g N m^{-2} (24 d)$^{-1}$ at the end of 3 and 5 yr, respectively. At the end of 6 yr, tillage regime caused a significant redistribution with depth of mineralizable N (Table 3). Following barley, mineralizable N at a depth of 0 to 50 mm was greater in ZT than in CT, but was not different among tillage regimes at 50 to 125 and 125 to 200 mm. Following fallow, however, mineralizable N in CT was 50% greater than in ZT at the 0- to 50-mm depth, 13% greater at the 50- to 125-mm depth, and 36% greater at the 125- to 200-mm depth. It appears that tillage during the fallow in CT was more effective in accumulating easily decomposable N substrates than the chemical fallow in ZT. Soil disturbance is known to result in an increase in inorganic N due to stimulation of mineraliza-

tion (Carter and Rennie, 1984). Inorganic soil N to a depth of 200 mm following fallow was 6.2 g N m^{-2} in CT and 4.7 g N m^{-2} in RT and ZT. Inorganic soil N following barley was not different among tillage regimes and averaged 3.9 g N m^{-2}. The greater mineralizable N following fallow in CT than in RT or ZT was not expected, since C and N inputs were similar among tillage regimes and previous research indicated that mineralizable N is often greater under ZT than under CT (Carter and Rennie, 1982; Doran, 1987; Franzluebbers et al., 1994). This unexpected finding may have been the result of increased intensity of drying–wetting and higher temperature of the soil under CT than under ZT during the fallow phase that rendered more native organic N mineralizable. The greater inorganic soil N and mineralizable N contents in CT than in RT and ZT indicate that application of more N fertilizer may be necessary to achieve optimum yields in this soil during the conversion of previously tilled soil to RT or ZT, at least if fallow is included in the rotation. Fertilizer N requirement of maize (*Zea mays* L.) was 6.8 g N m^{-2} (40%) greater under ZT than under CT in Maryland (Meisinger et al., 1985). In Texas, fertilizer N requirement of sorghum [*Sorghum bicolor* (L.) Moench] was 45% greater under ZT than under CT in the beginning, but became similar under both tillage regimes at 10 yr (Franzluebbers et al., 1995a).

The C/N ratio of the mineralizable fraction during 24 d of incubation following barley was not different among tillage regimes, but following fallow was lower in CT and RT than in ZT at the 0- to 50-mm depth (Table 3). This result indicates that when soil is disturbed with CT or RT and is not cropped, the flow of C and N through the mineralizable fraction becomes less stable, which may decrease the conservation of C and N in the long term. The C/N ratio of the mineralizable fraction reflects the C/N ratio of the organic material being decomposed in the soil under standard conditions. A C/N ratio of the mineralizable fraction greater than ≈15 at the 0- to 50-mm depth suggests that relatively N-poor crop residues and SOM fractions were present, especially following barley. The quality of mineralizable substrates (i.e., N concentration) was higher with soil depth. The greater C/N ratio at the 0- to 50-mm depth following barley compared with following fallow in CT and RT suggests that rhizodeposition and crop residue input led to a conservation of soil N in a slow-releasing organic form, rather than as inorganic soil N, which could be susceptible to leaching or denitrification loss if unused by crops.

SUMMARY AND CONCLUSIONS

Conversion of previously tilled soil to RT or ZT in northern Alberta had relatively small effects on SOM pools during 6 yr. Tilled fallow in CT led to both higher inorganic soil N and mineralizable N, such that less N fertilizer would be required to achieve optimum yields following fallow than with RT or ZT. Soil organic C was not significantly affected, but SMBC and BSR tended to be higher with ZT than with CT, especially at the

soil surface, indicating that conservation of C was slowly occurring. The large amount of SOC present in this northern soil may have limited measurable changes in total SOM. The portion of SOC as SMBC and BSR in this soil was less than half of soils in warmer regions, suggesting that more of the SOM was resistant to decomposition and that SOM loss due to cultivation or SOM accumulation due to reduction in tillage intensity will be slower. The slower rate of change in SOM pools requires that soil management practices in northern regions be evaluated in longer term studies.

ACKNOWLEDGMENTS

REFERENCES

Anderson, J.P.E. 1982. Soil respiration. p. 837–871. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Angers, D.A., A. Pesant, and J. Vigneux. 1992. Early cropping-induced changes in soil aggregation, organic matter, and microbial biomass. Soil Sci. Soc. Am. J. 56:115–119.

Arshad, M.A., K.S. Gill, and G.R. Coy. 1994. Wheat yield and weed population as influenced by three tillage systems on a clay soil in temperate continental climate. Soil Tillage Res. 28:227–238.

Arshad, M.A., K.S. Gill, and G.R. Coy. 1995. Barley, canola, and weed growth with decreasing tillage in a cold, semiarid climate. Agron. J. 87:49–55.

Arshad, M.A., M. Schnitzer, D.A. Angers, and J.A. Ripmeester. 1990. Effects of till vs no-till on the quality of soil organic matter. Soil Biol. Biochem. 22:595–599.

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185–193.

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58:777–786.

Bundy, L.G., and J.J. Meisinger. 1994. Nitrogen availability indices. p. 951–984. *In* R.W. Weaver et al. (ed.) Methods of soil analysis. Part 2. SSSA Book Ser. 5. SSSA, Madison, WI.

Campbell, C.A., V.O. Biederbeck, M. Schnitzer, F. Selles, and R.P. Zentner. 1989. Effect of 6 years of zero tillage and N fertilizer management on changes in soil quality of an Orthic Brown Chernozem in southwestern Saskatchewan. Soil Tillage Res. 14:39–52.

Carter, M.R., and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62:587–597.

Carter, M.R., and D.A. Rennie. 1984. Nitrogen transformations under zero and shallow tillage. Soil Sci. Soc. Am. J. 48:1077–1081.

Dalal, R.C. 1989. Long-term effects of no-tillage, crop residue, and nitrogen application on properties of a Vertisol. Soil Sci. Soc. Am. J. 53:1511–1515.

Dalal, R.C., P.A. Henderson, and J.M. Glasby. 1991. Organic matter and microbial biomass in a Vertisol after 20 yr of zero-tillage. Soil Biol. Biochem. 23:435–441.

Doran, J.W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fertil. Soils 5:68–75.

Follett, R.F., J.W.B. Stewart, and C.V. Cole (ed.). 1987. Soil fertility and organic matter as critical components of production systems. SSSA Spec. Publ. 19. SSSA, Madison, WI.

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1996. Determination of microbial biomass and nitrogen mineralization following rewetting of dried soil. Soil Sci. Soc. Am. J. 60:1133–1139.

Franzluebbers, A.J., F.M. Hons, and V.A. Saladino. 1995a. Sorghum, wheat and soybean production as affected by long-term tillage, crop sequence and N fertilization. Plant Soil 173:55–65.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1994. Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58:1639–1645.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1995b. Tillage and crop effects on seasonal dynamics of soil CO_2 evolution, water content, temperature, and bulk density. Appl. Soil Ecol. 2:95–109.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1995c. Tillage-induced seasonal changes in soil physical properties affecting soil CO_2 evolution under intensive cropping. Soil Tillage Res. 34:41–60.

Havlin, J.L., D.E. Kissel, L.D. Maddux, M.M. Claassen, and J.H. Long. 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54:448–452.

Ismail, I., R.L. Blevins, and W.W. Frye. 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58:193–198.

Jenkinson, D.S., and D.S. Powlson. 1976. The effects of biocidal treatments on metabolism in soil. V. A method for measuring soil biomass. Soil Biol. Biochem. 8:209–213.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill, New York.

Karlen, D.L., D.C. Erbach, T.C. Kaspar, T.S. Colvin, E.C. Berry, and D.R. Timmons. 1990. Soil tilth: A review of past perceptions and future needs. Soil Sci. Soc. Am. J. 54:153–161.

Kemper, W.D., and E.J. Koch. 1966. Aggregate stability of soils from western United States and Canada. USDA Tech. Bull. no. 1355. U.S. Gov. Print. Office, Washington, DC.

Meisinger, J.J., V.A. Bandel, G. Stanford, and J.O. Legg. 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage. I. Four-year results using labeled N fertilizer on an Atlantic Coastal Plain soil. Agron. J. 77:602–611.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 539–579. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Powlson, D.S., P.C. Brookes, and B.T. Christensen. 1987. Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. Soil Biol. Biochem. 19:159–164.

Rasmussen, P.E., and H.P. Collins. 1991. Long-term impacts of tillage, fertilizer, and crop residue on soil organic matter in temperate semiarid regions. Adv. Agron. 45:93–134.

SAS Institute. 1990. SAS user's guide: Statistics. Version 6 ed. SAS Inst., Cary, NC.

Staley, T.E., W.M. Edwards, C.L. Scott, and L.B. Owens. 1988. Soil microbial biomass and organic component alterations in a no-tillage chronosequence. Soil Sci. Soc. Am. J. 52:998–1005.

Voroney, R.P., and E.A. Paul. 1984. Determination of k_C and k_N in situ for calibration of the chloroform fumigation–incubation method. Soil Biol. Biochem. 16:9–14.

Whipps, J.M. 1990. Carbon economy. p. 59–97. *In* J.M. Lynch (ed.) The rhizosphere. John Wiley & Sons, New York.